Engineering Management
Field Project

Is Integrated Gasification Combined Cycle with Carbon Capture-Storage the Solution for Conventional Coal Power Plants

By

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Acronyms

ASU	Air Separation Unit
CO_2	Carbon Dioxide
COE	Cost of Energy
CCS	Carbon Capture and Storage
COS	Carbonyl Sulphide
DOE	Department of Energy
EOR	Enhanced Oil Recovery
FGD	Flue Gas Desulfurization
GT	Gas Turbine
HHV	Higher Heating Values
HCN	Hydrogen Cyanide
HRSG	Heat Recovery Steam Generation
IGCC	Integrated Gasification Combined Cycle
KBR	Kellogg Brown and Roast
Kwhs	Kilowatt Hours (Unit of Electricity)
KWe	Kilowatt of Electricity
LHV	Lower Heating Values
LGTI	Louisiana Gasification Technology Inc.
MIT	Massachusetts Institute of Technology
MW	Mega Watt
NI-Sets	Nickel based Solvents
NOx	Nitrogen Oxides
NH_3	Ammonia

NGCC	Natural Gas Combined Cycle
NSPS	New source Performance Standards
O&M	Operation and Maintenance
PC	Pulverized Coal
PM	Particulate Matter
PM10	Particulate Matter smaller than 10-microns
(U)SCPC	(Ultra) Super Critical Pulverized Coal
SCR	Selective Catalytic Reduction
Syn	Synthetic
SO_2	Sulphur Dioxide

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Executive Summary

Electric power generation and distribution has become an important part of our day-to-day activities. However, with the ever-growing awareness of environmental concerns as well as higher air emission and water standards, this industry has been under constant pressure to find better, more economical solutions for generating electric power. Coal is one fuel that powers about 50% of our electricity-generating facilities and is available in abundance compared with some other fuels used in the power industry.

Most pulverized coal plants are subcritical and use conventional technology. However, there are more modern super-critical and ultra super critical pulverized coal plants that use advanced technology, resulting in better efficiency and lower emissions. Integrated gasification combined cycle (IGCC) plants are relatively new and offer high efficiencies and reduced emissions. The biggest advantage with these plants is the ability and ease to capture carbon dioxide. Hence, they are referred to as capture ready, with comparatively much lower costs for capturing greenhouse gas (CO_2). Despite the promise of this technology, it is still being developed and tested and is not half as mature as pulverized coal plant technologies.

IGCC power plants have much higher capital and overall costs than pulverized coal (PC) plants. As time goes by, however, this technology will improve and further mature. Thus, the economic gap between these two power plant technologies will be reduced. The IGCC operating and maintenance costs also will go down with time. At present, costs for both super critical and IGCC plants are similar, but numerous unknowns associated with the IGCC plants could drive the costs of these plants up. The emissions for most gases are much lower with IGCC than with PC coal plants.

Future regulations for the greenhouse gas CO_2 will drive up the trading costs for CO_2. Since IGCC plants are capture ready, it will be much cheaper to capture CO_2 with IGCC than with PC coal plants. This is one of the greatest selling points of IGCC, in addition to its advantages in terms of emissions and efficiency.

Economics is the biggest hurdle for IGCC power plants at present, as well as the unknowns and lack of maturity associated with the technology. Even though there is an intense discussion about carbon capture and storage, as of today there is not even a single IGCC plant with a carbon capture and storage facility. However, some of the CCS technologies have been tried for some industrial plants.

Despite all the uncertainties attached to IGCC, this technology used along with Carbon capture and storage (CCS) still holds great potential and has a bright future. What is needed at present are some additional incentives in the form of subsidies from federal, state and local government.

Chapter 1 – Introduction

1.1 General Introduction

A power plant is an industrial facility involving a complex of structures, machinery and associated equipment for generating electric power by converting one form of energy into electrical energy. The form of energy being converted into electricity could come from various sources. The first power plant was the Holborn Viaduct of the Edison Company (Thomas Alva Edison Biography). This plant, based on the direct current principle, became operational in 1882. The Brighton Power Plant, which opened in 1887 (First Power Plants), was the first to use alternating current, a principle that was supported by Nikola Tesla and George Westinghouse. Since then, the electric power generation and distribution industry has come a long way, becoming a vital part of our lives and day-to-day activities through lighting, heating, cooling systems, communication systems, and industrial and commercial applications.

Developments in power generation have been driven by economics, technological advancements, and government regulations. These diverse forces have produced generation and distribution systems that are reliable, safe, environmentally acceptable, and suitable for service throughout the world. Yet with the ever-growing awareness of environmental concerns as well as higher air emission and water standards, this industry has been under constant pressure to improve the performance of power plants.

1.2 Types of Power Plants

1.2.1 Based on Energy Source

The types of power plants below are defined according to where the base source of energy is coming from.

- Coal-Fired Power Plants
- Diesel Engine Power Plants
- Hydroelectric Power Plants
- Natural Gas Power Plants
- Nuclear Power Plants
- Solar Power Plants
- Wind Power Plants
- Geothermal Power Plants

1.2.2 Based on the Function Performed

Three main types of power plants are categorized according to the functions they perform. These are called “base load,” “intermediate,” and “peaking” facilities.

- Base Load– These plants run continuously to supply power.
- Intermediate – These run less often than base load, but run most of the time.
- Peak – These usually run when customers are using high amounts of electricity, e.g., in summer.

1.2.3 Based on the Type of Prime Mover Installed

- Steam turbine plants use the dynamic pressure generated by expanding steam to turn the blades of a turbine. Almost all large non-hydro plants use this system. About 90% of all electric power produced in the world is by use of steam turbines (Wiser 2000).

- Gas turbine plants use the dynamic pressure from flowing gases (air and combustion products) to directly operate the turbine. Natural-gas fueled (and oil fueled) combustion turbine plants can start rapidly and so are used to supply “peak” energy during periods of high demand, though at higher cost than base-loaded plants. These may be comparatively small units, and sometimes completely unmanned, being remotely operated.

- Combined cycle plants have both a gas turbine fired by natural gas, and a steam boiler and steam turbine, which use the hot exhaust gas from the gas turbine to produce electricity. This greatly increases the overall efficiency of the plant, and many new base load power plants are combined cycle plants fired by natural gas.

- Internal combustion reciprocating engines are used to provide power for isolated communities and are frequently used for small cogeneration plants. Hospitals, office buildings, industrial plants, and other critical facilities also use them to provide backup power in case of a power outage. These are usually fuelled by diesel oil, heavy oil, natural gas and landfill gas.

- Hydro Power Plants use the energy of water stored behind the dams to turn the blades of turbine which turns the turbine to produce electricity. Water stored behind the dam uses the gravity once the intake gates are opened and water flows through the penstock.

1.3 Present Scenario

Coal is the single largest source of U.S. electricity production, approximately 50% over that of other sources used for production of electricity (U.S. Energy Information Administration 2010). Natural gas contributes about 24% and nuclear is in the range of 20%, based on average from the past few years.

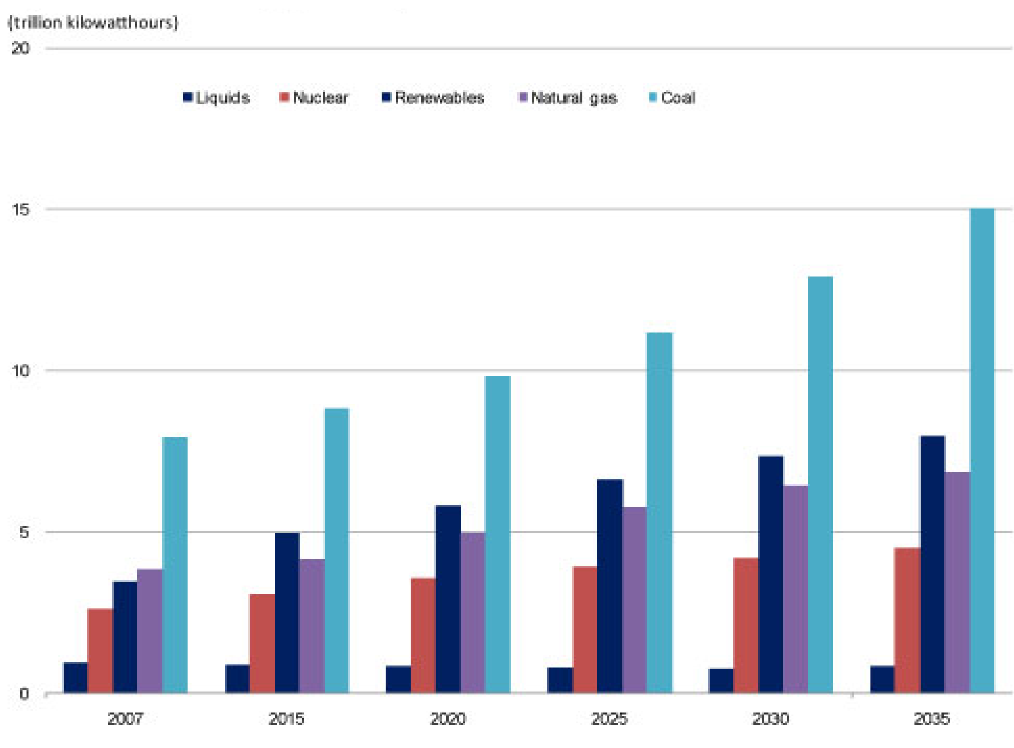


Fig. 1 – World Net Electricity Generation by Fuel, 2006-2030. Reprinted from U.S. Energy Information Administration. 2010. International Energy Outlook 2010. U.S. Department of Energy.

According to the report "International Energy Outlook 2010" by the U.S. Energy Information Administration, world net electricity generation will increase by 87%, from 18.8 trillion kwhs in 2007 to 25.0 trillion kwhs in 2020 and 35.2 trillion kwhs in 2035. In 2007, coal-fired generation accounted for 42% of world electricity supply; in 2035, its share will increase slightly to 43%. Sustained high prices for oil and natural gas make coal-fired generation more attractive economically, particularly in nations that are rich in coal resources, including China and India. Coal and natural gas are the second and third fastest-growing sources of energy for electricity generation in the projection (U.S. EIA, 2010). However, the outlook for coal, in particular, could be altered substantially by any future national policies or international agreements that aim to reduce or limit the growth of greenhouse gas emissions.

1.4 Coal Plants and IGCC-CCS Power Plants

1.4.1 Coal Plants

In the simplest terms, a conventional coal plant [i.e. pulverized coal (PC)] can be defined as a three-stage process, as explained below. The first conversion of energy takes place in the boiler. Coal is pulverized and then burnt in the boiler furnace to produce heat. Carbon in the coal and oxygen in the air are combined to produce carbon dioxide and heat. The second stage is the thermodynamic process. The heat from combustion of the coal boils water in the boiler to produce steam. In a modern power plant, boilers produce steam at a high pressure and temperature. The steam is then piped to a turbine. The high pressure steam impinges and expands across a number of sets of blades in the turbine. The impulse and the thrust created rotate the turbine. The steam is then condensed and pumped back into the boiler to repeat the cycle. In the third stage, rotation of the turbine rotates the generator rotor to produce electricity based on Faraday's principle of electromagnetic induction.

1.4.2 IGCC-CCS Power Plants

Integrated gasification combined cycle is a technology that converts the hydrocarbons or coal into synthetic gas (syngas) by applying heat under pressure in the presence of steam, which is then used as a fuel in combustion turbine. This syngas is cleaned of its hydrogen sulphide, ammonia and particulate matter before burning in a combustion turbine. Exhaust heat from the combustion turbine is recovered and used to boil water, creating steam for a steam turbine-generator. The plant is called integrated because its syngas is produced in a gasification unit, which has been optimized for the plant's combined cycle. Electric power is produced from both the gas and steam turbine generators. By removing the emission-forming constituents from the syngas under pressure before combustion in the power block, an IGCC power plant produces very low levels of criteria air pollutants (NOx, SO_2, and PM) and volatile mercury. Overall, this results in not only lower emissions of sulphur dioxide, mercury and particulate matter, but also improved efficiency compared with conventional coal plants (Hutchinson 2009).

The nomenclature IGCC refers to a design based upon a: 1. integrated, 2. gasification island, and 3. combined cycle power block.

There are many variations to the basic IGCC design (especially when it comes to "integration" between the gasifier-island, air separation unit (ASU), and power block). Nonetheless, the following observations can be made:

- It is the general consensus among IGCC plant designers that the preferred design today is one in which the ASU derives 25 to 50% of its oxygen supply from the gas turbine compressor and the rest from a separate air compressor (Hutchinson 2009).
- Pressurized gasification is generally preferred to avoid large auxiliary power losses for compression of the syngas. (High-pressure oxygen-blown gasification also provides advantages if/when CO_2 capture is mandated at a later date.)
- Entrained-flow gasifiers that operate in the higher-temperature slagging regions have been selected for the majority of IGCC project applications. A major advantage of using high-temperature entrained-flow gasifiers in an IGCC project is that they avoid tar formation and its related problems. The high reaction rate also allows single gasifiers to be built with large gas outputs sufficient to fuel the large commercial gas turbines now entering the marketplace

1.5 Scope

The scope of the present study revolves around the Conventional Coal Plants and Integrated Gasification Combined Cycle coal plants. The aim of the study is to review the literature on these coal plants and perform a comparison of their economic and environmental aspects. Economic criteria would involve capital and operating costs as well as cost of electricity as final product. Environmental aspects would include criteria air pollutants, mercury emissions, solid wastes and carbon dioxide emitted into the atmosphere. IGCC with Carbon Capture and Storage (CCS) is comparatively new to the industry and different people have varying opinions on this new technology. Thus, the author of this field project will examine the different aspects of this new technology and assess its viability.

Chapter 2 – Literature Review

2.1 Introduction

An extensive literature review has been carried out using the parameters defined for this project. IGCC with carbon capture and storage is still new to the power plant industry and people have different opinions about the technology. Since the capital costs for these power plants run into the billions and take 3 to 5 years to complete, it is not easy to experiment with these projects. Environmentalists, regulators, financial sponsors, and utility companies each have their own perspective when looking at these issues. Thus, the research reviewed was literature available from existing power plants, information published by the Department of Energy (DOE) and actual data posted by utility companies as well as companies providing gasification technologies.

A literature review was conducted through the DOE's website, the Google search engine and Wilson Omni search engines using the keywords such as "IGCC power plants," "IGCC economics," "IGCC financial aspects," "IGCC and regulation," "emissions for IGCC," "carbon capture and sequestration for IGCC," and "IGCC capital costs and IGCC electricity production costs." In addition, literature available in the Library of Power Division at the author's company has been used. This literature includes various power magazines and reports.

2.2 Economic Aspect

Economics is a critical factor in determining the pace of deploying IGCC power plants. At the same time, it is not easy to figure out the various costs involved and compare them. Factors such as capital costs, availability/reliability, operation & maintenance costs, relative coal prices, and the future cost of burning fuels all play crucial role in economics.

The Energy Policy Act of 2005 (Energy Justice Network 2007) enacted during the Bush era included $1.8 billion for “clean coal,” plus billions in federally guaranteed loans for IGCC. In June 2001, the Government Accountability Office (U.S. GAO, 2001) found that of the 13 “clean” coal projects examined, 8 had serious delays or financial problems, 6 were behind schedule by 2-7 years, and 2 projects went bankrupt and were abandoned. Bush administration policies ramped up the push for “clean” coal. IGCC “uncertainties” include lack of standard plant design, no performance guarantees, and high capital costs. IGCC veteran Stephen D. Jenkins testified in January 2007 (Dairyland Power Cooperative, 2008) that IGCC technology will not be ready for 6-8 years, has limited performance and emissions guarantees, and that commercial-scale CO_2 capture and storage has not been demonstrated.

In one study (Booras and Holt 2004), the economics of the pulverized coal plants (subcritical and supercritical) were compared with IGCC and natural gas combined cycle plants (NGCC). While numerous factors and assumptions go in making such a comparison, including fuel cost, emission control requirements, capital cost, load factor, local labor rates, expected reliability/availability and the life cycle for the plant, the study still provided a platform to compare these different plants. See **Appendix A** for a detailed table outlining cost, performance and economics for a nominal 500MW power plant.

Plant capacity factor has a significant impact on the cost of energy (COE), especially for capital intensive coal-fired technologies. Figure 2 below shows the impact of capacity factor on the constant dollar levelized COE for the bituminous coal-based technologies. A spare gasifier for the IGCC case would not be necessary unless the plant was required to operate at very high capacity factors. IGCC plants without a spare gasifier are projected to have equivalent availabilities in the low 80%'s, whereas inclusion of a spare gasifier is expected to increase the IGCC plant equivalent availability to the low 90%'s. The curves show that PC plants have a slight COE advantage over an IGCC plant without a spare gasifier throughout the range of capacity factors. This PC plant COE advantage becomes larger if the IGCC plant incorporates a spare gasifier. The coal-based technologies become preferable over NGCC at capacity factors over 78-80%.

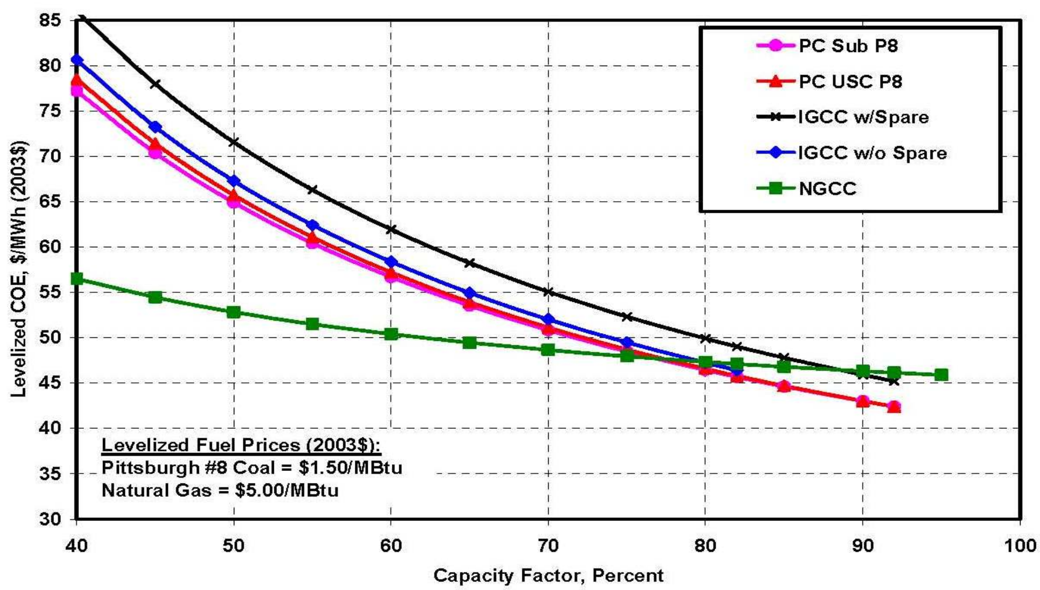


Fig. 2 – Impact of Capacity Factor on Levelized COE. Reprinted from Booras, George, and Neville Holt. 2004. Pulverized coal and IGCC plant cost and performance estimates.

If a spare gasifier is required in order to operate at IGCC equivalent availabilities approaching 90%, the IGCC COE will be increased by $2.7 to 2.9/MWh, for Pittsburgh #8 and Illinois #6 coals, respectively. IGCC technology does not have the established power industry operating history and historical precedents of the conventional pulverized coal plants. Additional cost elements and higher perceived risk factors for IGCC also can affect the project development schedule and financing charges and increase the owners' costs to a greater extent than for PC. One of the major factors is environmental permits. Even though on the one hand industry talks about increased efficiency and reduced emissions, it seems to take long periods to acquire the necessary permits and secure financing. If IGCC is to become a real option for coal-based power generation, some additional economic incentives or environmental relief may be required.

The super critical pulverized coal plant (SCPC) is the closest competitor to IGCC. Around the year 2000, the specific investment (IEA Energy Technology Network 2010) cost was approximately $1500/kWe (2008 US$). In 2008, the investment cost of state-of-the-art SCPC power plants was approximately $2200/kWe. As SCPC is a mature technology, its investment cost may decrease moderately based on technology learning. The following costs are predicted (IEA 2010) over the next two decades: $2200/kWe in 2010 (based on current experience), $2000/KWe in 2020, and $1800/KWe in 2030 (based on learning effects).

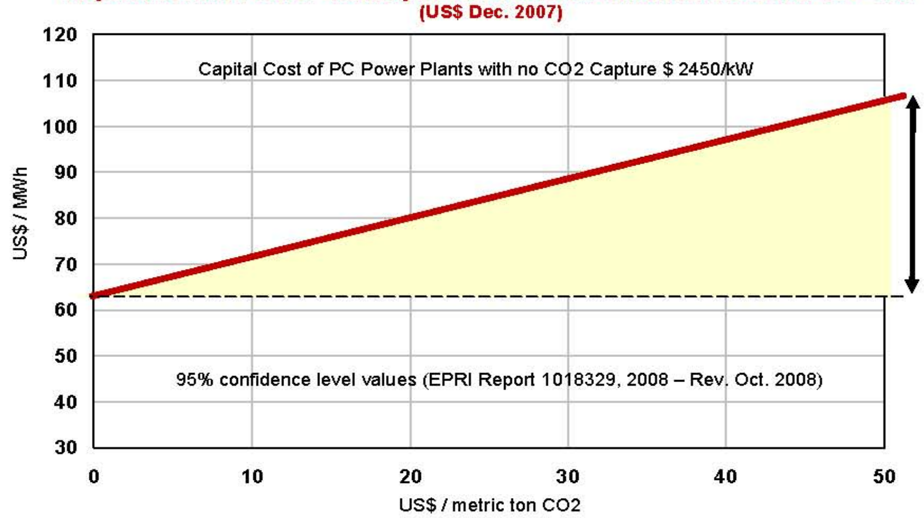
When compared with pulverized coal, the investment cost of coal-based IGCC plants is high, i.e. $3700/KWe. Technological learning is expected to have a more important impact on future IGCC investment costs. Projections suggest a decline from some $3700/KWe in 2010 (70% more than PC power) to $2800/KWe in 2020 (40% more than PC power) and to $2200/KWe in 2030 (20-25% more than PC power). Technology learning effects rely on the future availability of high-capacity gasifiers, more efficient gas cleaning systems, and high efficiency gas turbines. The IGCC investment cost is relatively high.

The operation and maintenance cost (O&M cost, expressed in $/KWe per year) is estimated at 4% of the investment cost per year for both SCPC and IGCC, but the IGCC plants may face higher O&M costs because of a lower technology maturity. For Ultra Super Critical Pulverized Coal (U-SCPC) and standard plants, the O&M cost is estimated by IEA (2010) at $88/KWe per year in 2010, $80/KWe in 2020, and $72/KWe in 2030, while for IGCC plants, the O&M cost is estimated at $148/KWe per year in 2010, $112/KWe in 2020, and $88/KWe in 2030. Table 1 below provides essential data comparing various aspects including efficiency, cost and emissions for pulverized coal and IGCC plants.

Table 1– Summary Table - Key Data and Figures for Coal-based Power Technology

Technical Performance	Typical current international figures	
Energy input	Hard coal or lignite; possible biomass co-firing up to 10–20% of energy	
Output	Electricity	
Technologies	(Ultra)supercritical plants (U)SCPC	IGCC
Efficiency, %	46%	46%
Construction time, months	Minimum 42; Typical 48; Maximum 54	
Technical lifetime, yr	40	
Load (capacity) factor, %	Typical 75–85; Maximum 90	
Max. (plant) availability, %	92	
Typical (capacity) size, MW_e	600–1100	250–1200
Installed (existing) capacity, GW_e	1,260	1
Environmental Impact		
CO_2 and other GHG emissions, kg/MWh	730–850	700–750 (new IGCC plant)
SO_2, g/MWh	110–250	50
NO_x, g/MWh	180–800	70
Particulates, g/MWh	8–25	5–25
Solid waste (fly ash), kg/MWh	60–70	60–70
By-products	Gypsum	Sulphur
Costs		
Investment cost, including interest during construction, $/kW (PC / IGCC)	2000 – 2500; Typical 2200 (2010)	3500 – 4000; Typical 3700 (2010)
O&M cost (fixed and variable), $/kW/a	88	148
Fuel cost, $/MWh	15–25	15–25
Economic lifetime, yr	25	
Interest rate, %	10	
Total production cost, $/MWh (PC / IGCC)	60 – 70 / Typical 65	90 – 100; Typical 95
Market share	40% of global electricity output	Currently negligible

Projected Levelized Cost of Electricity for Pulverized Coal Combustion vs. Cost of CO2 - 2015 (US$ Dec. 2007)



Data Projections	2010		2020		2030		
Technology	(U)SCPC	IGCC	(U)SCPC	IGCC	SC(USC)	IGCC	
Net Efficiency (LHV)	46%	(46)	50%	52%	50%	52%	
Investment cost, including interest during construction, $/kW (PC / IGCC)	2200	3700	2000	2800	1800	2200	
Total production cost, $/MWh	65	95	62.5	75	60	65	
Market share, % global electricity output	35		30 – 35		25 – 35		

Table 1– Summary Table – Key Data and Figures for Coal-based Power Technology - Reprinted from IEA Energy Technology Network 2010

2.3 Economics of IGCC with CCS

In the current non-carbon constrained economy, it is cheaper to build and operate a pulverized coal plant than it is to build an IGCC plant. However, several recent studies indicate that if the United States were to pass sufficiently stringent carbon regulation policies, this result would be reversed. In a carbon-regulated world, traditional pulverized coal power plants would have to reduce carbon emissions, buy carbon credits to offset emissions, sequester emissions or pay a financial penalty on emissions. Carbon capture technology can allow power generators to reduce emissions at a reasonable cost, and this technology can be added more easily and inexpensively to IGCC plants than to PC plants.

According to a study (Francis, Grodon, Hanniman & Rhodes –COWS 2007), building and operating a SCPC plant in a carbon-regulated environment costs $10 per MW-hour more if there are no restrictions on carbon emissions. Thus, the question arises as to what level of regulation in the carbon capture industry would be required for IGCC to be financially preferable over PC. An MIT study (Sekar et al. 2005) puts the tipping point at $23.28 per ton of carbon dioxide emission. The study admits that this is a rather steep fee that might prevent the technology from gaining immediate political support. However, the study notes that carbon dioxide emissions were trading at $30 per ton under the European cap-and-trade system at the time of publication. Once the United States enters the carbon trading market, it will become part of a global trading system in which carbon dioxide has value—value that will probably only go up as the threat of global warming is better understood.

Under various research programs sponsored by DOE, a prime focus has been on the cost of carbon sequestration. TDA Research, Inc. (Yu, Black and Rardin 2005) teamed up with

Halliburton Kellogg Brown & Root (KBR), and Louisiana State University at Baton Rouge and contracted with DOE on CO_2 capture. The impact of using the nickel-based sorbent (Ni-SETS) process and sorbent to capture and sequester CO_2 from a coal-fired IGCC plant was analyzed. The results of this study revealed that the cost of capture ranged from $5.37/ton of CO2 for an IGCC plant topped with a high-temperature membrane to $12.48/ton of CO_2 for the IGCC plant topped with a low temperature membrane. The corresponding capture efficiencies were nearly 100% and 82%, respectively. In a separate study (Spiwak 2004), it was estimated that CO_2 sequestration cost ratios of IGCC, PC (or Fluidized Bed) and CCGT are about 1:1.8:3.

2.4 Environmental Aspect – Emissions

IGCC plants have achieved the lowest levels of criteria pollutant air emissions (NOx, SOx, CO, PM10) of any coal- fueled power plants in the world. Emissions of trace hazardous air pollutants are extremely low, comparable with those from direct-fired combustion plants that use advanced emission control technologies. Discharge of solid byproducts and wastewater is reduced by roughly 50% versus other coal-based plants, and the by-products generated (e.g., slag and sulfur) are environmentally benign and can potentially be sold as valuable products. Table 2 below compares an existing super critical pulverized coal plant with an IGCC plant under construction in terms of efficiency and emissions.

Plant Parameters EOn	Maasvlakte, Netherlands	Edwardsport, Indiana – USA
Type of plant	SCPC	IGCC
In service	2012	2012
Fuel	Bitum.coal	Bitum. Coal
Availability, %	91	85
Turbine power, MWe	1,100	795
Internal load, MWe	45	163
Net capacity, MWe	1,055	632
Net efficiency, %	46.0	44.0
Coal use, t/day	7,350	
SO2 emissions	40(0.11)	NA(0.05)
mg/Nm3 (g/kWh)		
DeSOx, %	98	99+
NOx SCR@15%O2,		
mg/Nm3 (g/kWh)	65(0.18)	NA(0.07)
PM emissions		
mg/Nm3, (g/kWh)	3(0.008)	NA(0.026)

Table 2 – Technical Parameters for SCPC and IGCC Plants. Reprinted from IEA Energy Technology Network 2010. Coal fired power. Technology brief E01- Energy Technology Systems Analysis Program.

Table 3 below compares the criteria air pollutant emissions from a state-of-the-art IGCC plant with the 2002 federal New Source Performance Standards (NSPS) for pulverized coal-fired power plants.

CRITERIA POLLUTANT	EXPECTED IGCC EMISSION LEVELS lb/10_6 Btu (lb/MWh)	NSPS LIMIT lb/10_6 Btu (lb/MWh)
SO2	**< 0.15 (0.5)**	**1.2 (None)**
NOx	< 0.1(1)	0.15 (1.6)
PM10	< 0.015(0.14)	0.03 (None)
CO	< 0.033 (0.3)	None (None)

Table 3 – IGCC Expected Emission Levels of Criteria Pollutants. Reprinted from Ratafia-Brown, Jay A. Lynn M. Manfredo, Jeff W. Hoffmann, Massood Ramezan, and Gary J. Stiegel. 2002. An environmental assessment of IGCC power systems. Paper presented at the Nineteenth Annual Pittsburgh Coal Conference, September 23-27, in Pittsburgh, PA.

Criteria Air Pollutants

SO_2

During the entrained gasification process in IGCC plants (Ratafia-Brown, et al. 2002), under high temperature and limited oxygen the sulphur in the coal is converted to hydrogen sulfide (H_2S), as well as a small amount of carbonyl sulfide (COS). These H_2S, COS and particulate contaminants are mostly removed from the syngas prior to combustion or other forms of fuel conversion (e.g., fuel cell). Acid gas removal equipment extracts 95-99% of the H_2S and COS from the fuel gas and converts it to a salable sulfur or sulfuric acid (H_2SO_4) byproduct. The small amount of residual sulfur that remains in the syngas is converted to SO_2 in the combustion turbine and released into the atmosphere in the primary stack gas or in the secondary stack gas from the sulfur recovery equipment. The commercial IGCC plants, Polk and Wabash River, achieve emissions below 0.15 lb $SO_2/10_6$ Btu heat input or greater than 97% sulfur reduction. These limits are much lower than the federal limits on SO_2 emission.

NOx

The gasification process differs significantly from the process used for pulverized coal plants (Ratafia-Brown, et al. 2002) with respect to the impact of chemically-bound nitrogen in solid fuels, like coal. Gasification, because it operates with a deficiency of oxygen, converts most of the fuel nitrogen into harmless nitrogen gas (N_2). While a small portion is converted to ammonia (NH_3), as well as small amounts of hydrogen cyanide (HCN) and thiocyanate, these water-soluble species are removed during fuel gas cooling and cleaning and are usually converted to nitrogen in the sulfur recovery process. Therefore, the fuel gas produced is virtually free of fuel-bound nitrogen. By maintaining a low fuel-air ratio (lean combustion) and adding a diluent (e.g., nitrogen from the air separation unit or steam), the flame temperature can be lowered to reduce the potential for NOx formation. IGCC NOx emissions of less than 0.1 lb/10_6 Btu (Duffy-Nelson, 1997) are quite low relative to the emissions of a PC plant with low-NOx burners (approximately 0.4 lb/10_6 Btu for a tangentially- fired boiler).

Particulate Emissions

Particulate control in gasification processes (Ratafia-Brown, et al. 2002) is highly efficient, as gasifiers operate at high pressure and generate a significantly smaller gas volume than coal combustion. Not only does the gasification process provide the inherent capability to remove most ash as slag or bottom ash, but the fly ash produced is concentrated in the smaller gas volume, which further assists in its cost effective collection. Both the Polk and Wabash River plants use a wet scrubber to efficiently capture fine particulates that are entrained in the syngas. Additional particulate removal occurs in the gas cooling operations and in the acid gas removal systems. As a result, very low particulate emission levels are achieved. The Wabash plant reported emissions of less than 0.012 lb/10_6 Btu heat input (0.088 lb/MWh output), while the Polk plant typically emits less than 0.015 lb/10_6 Btu. These emissions (Duffy- Nelson, 1997) are significantly less than the current federal NSPS requirement of 0.03 lb/10_6 Btu heat input.

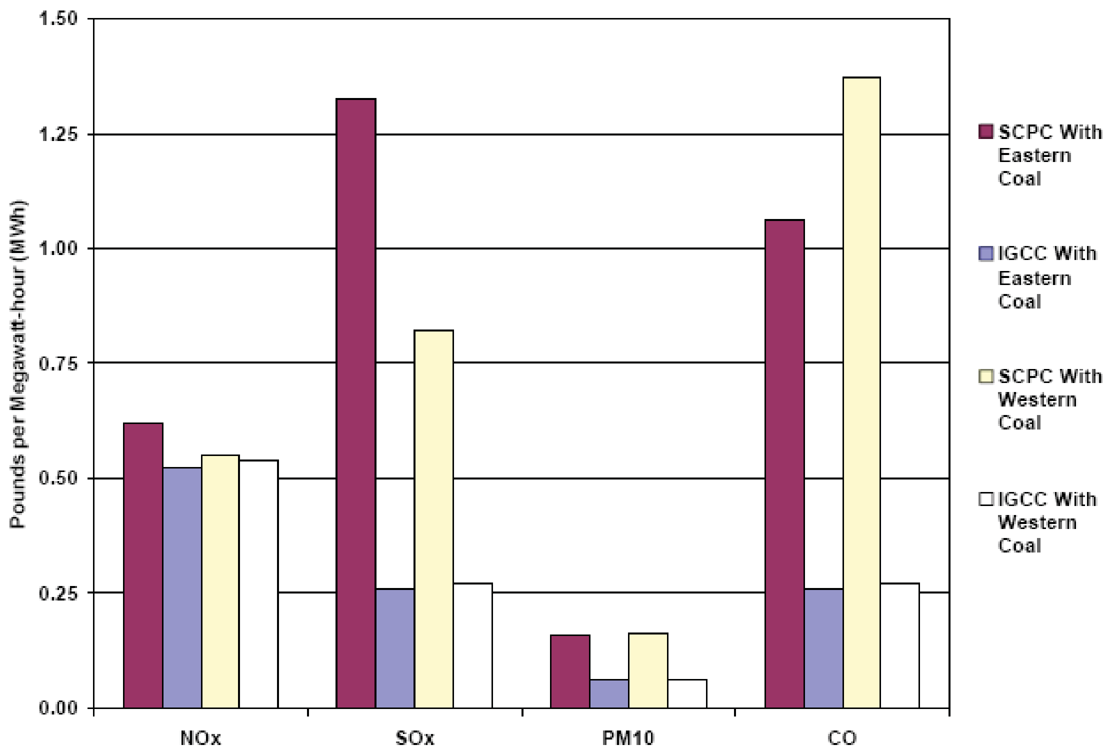


Fig. 3 – Other Pollutant Emission Rates, IGCC Vs PC. Reprinted from Francis, Grodon, Hanniman & Rhodes, 2007. IGCC with Carbon Capture and Storage-Opportunities and Challenges for Labor.

Lead Emissions

Lead, a semi-volatile metal (Ratafia-Brown, et al. 2002), is released from coal during combustion or gasification and partially volatizes and becomes enriched on fly ash particles of decreasing particulate size. Trace metal mass balance results for Louisiana Gasification Technology, Inc. (LGTI's) IGCC plant showed about one-third of the lead in the coal ended up in the gasifier slag and less than 5% as air emissions. The remaining lead was assumed removed in the particulate and acid gas cleanup systems and discharged with solid and liquid waste streams. Trace amounts of lead contained in coal can be efficiently removed in an IGCC plant with minimal discharge into the atmosphere. Lead discharged with the slag can be effectively sequestered, but the form of the lead species discharged in solid or liquid streams, from the plant's water treatment facility, is not known.

Mercury

Mercury is a particular problem in both combustion and gasification systems, since it primarily remains in the vapor phase due to its low boiling point (180^{o}F). Compared with combustion-based power plants, IGCC plants have a major advantage when it comes to mercury control. Commercial methods have been employed for many years that remove trace amounts of mercury from natural gas and gasifier syngas. Both molecular sieve technology and activated carbon beds have been used for this purpose, with 90 to 95% removal efficiency reported. Another DOE cost study was conducted for applying a packed-bed carbon adsorption system to an IGCC plant. Based on an 18-month carbon replacement cycle and 90% reduction of mercury emissions, the total cost of mercury reduction was estimated to be $3,412 per pound of mercury removed, which was projected to be about one-tenth the cost of flue gas-based supercritical pulverized coal mercury control.

Figure 4 below indicates that IGCC plants consistently emit less mercury per megawatt-hour than even the best pulverized coal plants (known as supercritical or SCPC), regardless of whether they are burning Eastern or Western U.S. coal.

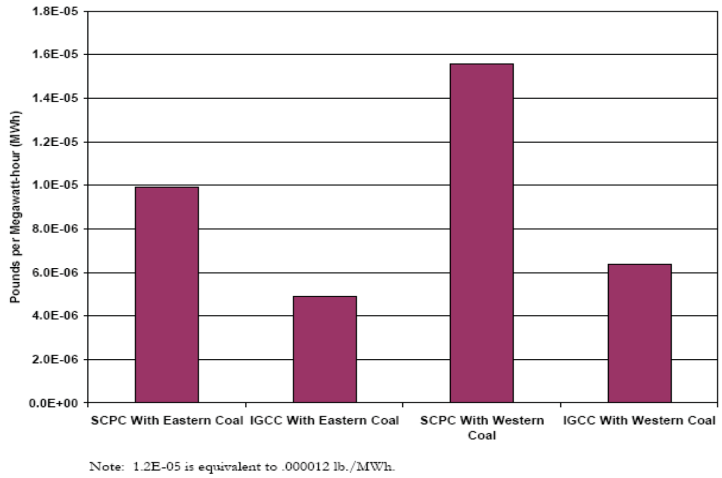


Fig. 4 – Mercury Emission Rates, IGCC vs PC. Reprinted from Francis, Grodon, Hanniman & Rhodes, 2007. IGCC with Carbon Capture and Storage-Opportunities and Challenges for Labor.

Other Environmental Benefits

Another environmental benefit of IGCC plants is the 25-40% (Francis et al. 2007) reduction in water use compared with pulverized coal plants. The primary reason is the large quantity of water required for steam generation and cooling from nearby water bodies. In addition, the sulfur and mercury removed from the syngas in an IGCC plant are contained in higher-concentration, lower-volume waste streams. Depending on the type of coal burned, IGCC plants produce 15-50% less waste volume than pulverized coal plants do. Also, IGCC plants produce slag that is vitrified, which makes it less prone to leaching from landfills into the environment.

This Chapter covered the economic aspects from operation and maintenance standpoint as well as construction of a new plant. It also reviewed the economics of IGCC with carbon capture and looked at environment aspects which involved emission of harmful gases and particulate matter into atmosphere based on comparison of the emissions for the two coal plants, pulverized coal plants and IGCC coal plants. In the next Chapter different technologies available in the market for the coal plants and Carbon capture with storage will be covered.

Chapter 3 – Procedure and Methodology

In this chapter, the latest working technologies for the two power plants: pulverized coal plants and integrated gasification combined cycle are covered in detail. Following the working technologies discussion, carbon capture and storage, emissions and economy are compared for the two different power plants.

3.1 Working Technology – Conventional Coal Plants

Pulverized coal combustion has been the conventional industry for several decades and is the most widely used technology in coal powered generation. The gas side typically operates at atmospheric pressure simplifying passage of materials through the plant. The main development in the PC combustion involves increasing plant thermal efficiencies by increasing the steam pressure and temperature at the inlet of steam turbine inlet (Nalbandian 2009). The three main types are:

- Sub-critical technology power plants
- Super-critical technology power plants
- Ultra super-critical technology power plants

Based on the main stream pressure, temperature and net efficiency, the above technologies can be summarized, as in Table 4 below. The definition of supercritical and ultra supercritical pressure and temperature can vary from one country to other, but the range shown in the table is frequently used and followed. In Europe, efficiencies are expressed based on lower heating value

(LHV) while in the U.S. they are expressed as higher heating values (HHV). The result is that, for virtually identical plant performance (coal in vs power out), the U.S. efficiency reported (HHV) would be 2-4% higher than European efficiency (LLV).

Pulverized Coal Power Plants	**Main Steam Pressure (Mega Pascal)**	**Main Steam Temperature, EC**	**Reheat Steam Temperature, EC**	**Efficiency % net, HHV basis**
Subcritical	< 22.1	Up to 565	Up to 565	33 – 39
Supercritical	22.1 - 25	540 – 580	540 – 565	38 – 42
Ultra Supercritical	> 25	> 580	> 580	> 42

Table 4: Approximate Pressure, Temperature and Efficiency for PC Technologies. Reprinted from Hermine Nalbandian 2009. Energia – Center for Applied Energy Research

With the extensive favorable experience in Europe, Japan and Korea using supercritical (SC) steam cycles over the past decade, their superior environmental performance and the relatively small cost difference between SC and subcritical plants, it is becoming more difficult to justify new subcritical steam plants. The ultra-supercritical plant level of technology maturity differs from that of the subcritical and supercritical and is used relatively rarely in North America. Currently, there are two of these plants, one each in Denmark and Japan, having efficiencies of 45% and 47%, respectively. Leading companies offering ultra-supercritical plants are mostly in Japan and include Hitachi, IHI, MHI and Mitsui.

The major components of pulverized coal (Booras and Holt 2004) units include coal-handling equipment, the boiler island, turbine-generator island, flue-gas desulfurization (FGD) system, fabric filter, bottom and fly ash handling systems, and a wet stack with no flue gas reheat. Also required are low NO_x burners and selective catalytic reduction (SCR) to reduce NO_x emissions to desired limits. The boiler island includes the coal pulverizers, burners, water wall-lined furnace, super-heater, re-heater, economizer, soot blowers, regenerative air heater, and axial-flow forced- and induced-draft fans. The turbine-generator island includes the main, reheat, and extraction steam piping, feed water heaters, condenser, mechanical draft cooling towers, boiler feed pumps, and auxiliary boiler.

3.2 Working Technology – IGCC Power Plants

There are many variations on the basic IGCC scheme, especially in the degree of process integration. It is the general consensus among IGCC plant designers today that the preferred design is one in which the air separation unit (ASU) derives part of its air supply from the gas turbine compressor and part from a separate air compressor. Three major types of gasification systems are used today (Environmental Footprints and Costs- Nexant Inc 2006):

- Moving bed,
- Fluidized bed, and
- Entrained flow

In a moving-bed gasifier, a bed of crushed coal is supported by a grate and the reactions between coal, oxygen, and steam take place within this bed. The gasifier operates at temperatures below the ash slagging temperature.

Fluidized-bed gasifiers also have a discrete bed of crushed coal. However, the coal particles are kept in a constant motion by the upward gas flow. The fluidized bed is maintained below the ash fusion temperature.

In entrained-flow gasifiers, finely pulverized coal particles concurrently react with steam and oxygen with very short residence time. These gasifiers operate at high temperature where the coal ash becomes a liquid slag. These units form the majority of IGCC project applications and include the coal/water-slurry-fed processes of GE Energy and ConocoPhillips, and the dry-coal-fed Shell process.

The basic configuration includes two trains of air separation units, two operating gasification trains, a single acid gas removal train, two combustion turbines and Heat Recovery Steam Generation (HRSG)'s and a single reheat steam turbine(Booras and Holt 2004). The gasification plant is sized to fully load the combustion turbines at 15°C (59°F). Natural gas is used for startup and as a backup fuel. The combustion turbines are designed for dual-fuel capability and natural gas can be used in the event of gasification plant outages.

Figure 5 below shows major characteristics of the three gasifiers.

See Appendix B for General Performance Comparison for IGCC and PC plants for bituminous, sub-bituminous and lignite coals.

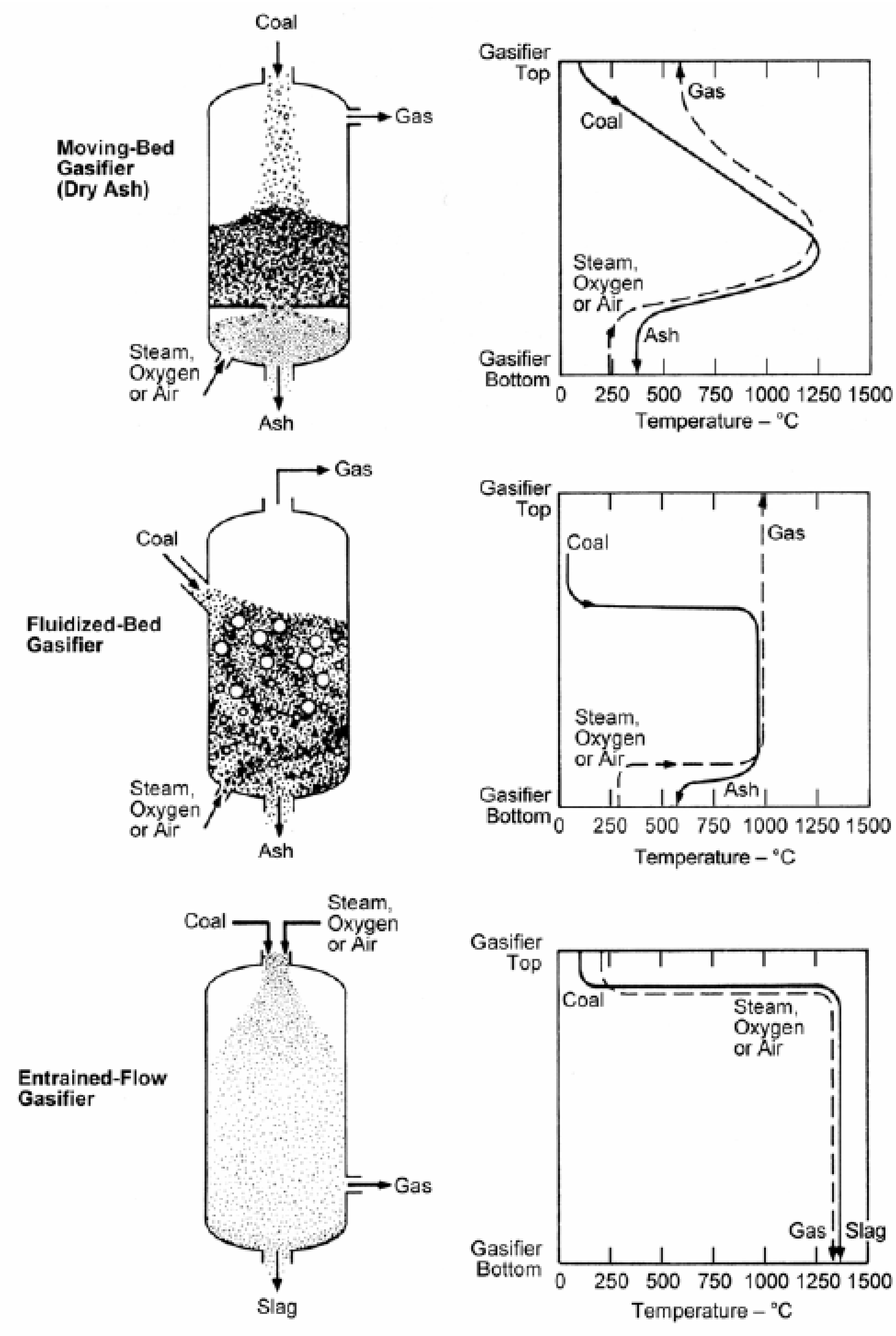


Fig. 5 – Major Gasification System Types. Reprinted from Nexant Inc 2006. Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies. EPA-430/R-06/006.

3.3 Carbon Capture and Storage

Carbon capture and storage (CCS) is one of the most important and controversial environmental benefits of IGCC plants. Carbon dioxide can be removed from the gas stream during IGCC process more readily than in a pulverized coal plant, where it needs to be removed from smokestack emissions. Therefore, IGCC plants have a major advantage over pulverized coal plants when it comes to carbon capture. Reduction is CO_2 contents into the atmosphere is a key advantage for addressing global warming. The captured CO_2 needs to be transported and stored safely. At present, it is possible to follow CCS methods, and some of them are currently being used in some non-IGCC facilities (Francis, Grodon, Hanniman & Rhodes, 2007).

- *Enhanced oil recovery (EOR):* CO_2 is injected into oil wells, where it pushes the oil up toward the surface. This process has been used for over 50 years, but until recently, the carbon dioxide has been allowed to vent to the air once it does its job. One large-scale permanent carbon storage/EOR project that currently exists is Weyburn Saskatchewan, which began in 2003 and sequesters over 1 million tons of carbon dioxide every year.
- *Injection into Underground Geological Formation:* CO_2 is injected as a fluid into deep geologic formations, such as saline aquifers; the formations chosen for carbon storage have natural cap rocks, such as shale, that prevent the CO_2 from leaking upward to re-enter the atmosphere. Over time, the liquid CO_2 dissolves into the aquifer fluids and forms new minerals, further reducing the ability of the CO_2 to leak upward. Two large projects currently employing this method of carbon storage are in Sleipner, Norway and In Salah, Algeria.

- *Enhanced coal bed methane recovery*: CO_2 is injected into un-mineable coal seams in order to push out the methane, leaving the CO_2 trapped below. The methane can then be refined and sold commercially. An important caveat about this storage method is that it has never been tested on a commercial scale.

Two other methods of carbon storage are not yet considered able to reliably store large quantities of CO_2. One is terrestrial storage, in which land management practices are altered to maximize the CO_2 intake from vegetation. A promising variation on terrestrial storage involves using biomass as a feedstock (see Table 5 on next page). The other is chemical conversion, in which CO_2 is chemically combined with other compounds to prevent its release into the atmosphere. Such materials might be safely used in construction.

Most of the proposed IGCC plants are considered “capture ready” and initially capture only 15-30% of CO_2 from the gas stream. Significant effort is required to modify a capture ready plant to one that actually captures a majority of CO_2. Another way to look at it is that with the increasing efficiencies for the supercritical and ultra supercritical pulverized coal plants, less coal is burnt to produce per unit electricity, thereby releasing fewer CO_2 emissions. These reductions could be in range of 18-20% (Booras and Holt 2004).

The economic standpoint at present is that it is cheaper to build and operate PC plants in this currently non-carbon constrained world. However, as the regulations on carbon narrow, and become stringent, IGCC with CCS would appear to be more efficient and environmentally sound.

3.4 Emissions & Economics

In the present study, the emissions examined are limited to NOx, SO_2 and particulate matter (PM). The pulverized coal plants are designed with wet limestone flue gas desulphurization (FGD) to remove 95% sulphur and are equipped with low NOx burners and selective catalytic reduction units to bring down NOx emissions to 0.1lb/MBtu fired (Booras and Holt 2004). Bituminous coal mercury is mostly captured in the FGD and hence does not require any additional mercury control steps.

IGCC plants are usually designed for well over 99% sulfur removal. In addition, the SCR in the HRSG section ensures that the SO_2 and NOx emissions from the gas turbine exhaust both are less than 2ppmv at 15% oxygen (equivalent to 0.006 lb/Mbtu) in the gas turbine flue gas. A bed of pre-sulfided activated carbon is used to remove >90% of the mercury from the syngas prior to sulfur removal and clean syngas being fed to the gas turbine.

Plant Emissions	PC Plants	IGCC Plants
SO_2 Control	A. Bituminous and lignite coals, wet limestone flue gas desulfurization and production of gypsum. B. Sub-bituminous coal, lime spray dryer desulfurization followed by fabric filter bag house and production of solid waste containing SO2 reaction products and ash	All coals, methyl di-ethanol amine (MDEA) gas cleaning and production of elemental sulfur.
Particulate Control	All coals, fabric filter bag-house.	All coals, high temperature metal filters. (The wet processing of the gas cleaning process adds to particulate removal downstream of the filters.)
NO_X Control	Combustion controls & SCR.	All coals, combustion controls with nitrogen dilution.

Table 5 – Emission-Procedure PC and IGCC Plants. Reprinted from Nexant Inc 2006. Environmental Footprints and Costs of Coal-Based Integrated Gasification Combined Cycle and Pulverized Coal Technologies. EPA-430/R-06/006.

Capital costs for the IGCC power plants are higher than the pulverized coal plants. Different estimates from various authors have been provided in the literature review. Based on assumptions and certain design parameters, capital costs for the IGCC plants are 20-47% higher than traditional coal plants. These costs, combined with those required for CO_2 capture and sequester, would further increase the costs for IGCC. However, the increase in cost would be more for the PC coal plants since IGCC are considered carbon capture ready and have higher efficiency than PC coal plants. Another important factor increasing the cost of IGCC plants is the spare gasifier that is required if higher availability in the range of 90% or more is needed. ***See Appendix B for Environmental Impact Comparison and Technology Cost Comparison for IGCC and PC plants for bituminous, sub-bituminous and lignite coals.***

Chapter-4 Results and Conclusion

The literature review and procedure and methodology chapters have presented numerous data based on reports and studies by different authors. As of 2007, there were only two IGCC power plants in the United States and two in Europe, while several others were either in the planning, permitting or construction stages. These plants are expected to open between 2012 and 2020. There are very few super critical pulverized coal plants being constructed in the United States, and ultra super critical plants are very rare. Of a total of 570 super critical and ultra super critical units at 430 power plants approximately one-third are in United States (IEA Energy Technology Network 2010). Various technical and economic factors go into making the decision of building a power plant and choosing the type and technology.

- Coal is the most abundant and cheap fuel available at present and will continue to be so; about 50% of electricity is produced using coal. Coal technology will survive and will be the right solution if it can provide more efficiency, better economy at start up and over the long term, lower operation-maintenance cost and lower emissions and other environmental challenges to keep up with ever tightening regulatory standards.

- Super critical and ultra supercritical pulverized coal plants are more efficient and have lower emissions compared with sub-critical conventional coal plants. Super critical technology is well established at present. The higher capital costs of these over sub critical plants are justified by better efficiency and lower emissions. The costs for these plants would lower as technology advances, but not by much since these technologies are close to maturity.

- Integrated gasification combined cycle (IGCC) capital costs are higher than costs for pulverized coal plants depending upon the type of PC plant. If a spare gasifier is desired to achieve higher availability of 90% or more, the capital costs of IGCC plants are expected to be 8-10% higher (Booras and Holt, 2004). Again, not many plants have been built to justify any of these estimates and there is a lot of uncertainty when it comes to IGCC technology. The IGCC is improving and will improve in coming years, so the cost will go down significantly compared with the matured technologies of PC plants, which may not go down much.

- The costs of supercritical and ultra-supercritical pulverized coal power plants (IES-ETSAP 2010) are expected to decline from $2200/kWe in 2010, to $2000/kWe in 2020, and to $1800/kWe in 2030. On the other hand, technology learning may significantly reduce the IGCC investment cost from $3700/kWe in 2010 (70% more than PC) to $2800/kWe in 2020, and to $2200/kWe in 2030 (20-25% more than PC).

- The operating & maintenance costs for SCPC and IGCC are estimated to be the same at about 4%, but due to lower technology maturity, IGCC might face higher costs.

- One of the greatest advantages of IGCC plants is their ability for capturing carbon more readily than PC plants. IGCC plants are designated as capture ready as production of CO_2 during the gasification process offers the opportunity for low cost CO_2 capture and storage. However, at the same time, CO_2 storage has not been fully established and is still being researched. Future anticipated regulations for reducing greenhouse gases and higher costs associated with CO_2 trading will eventually give a boost to IGCC plants that have an advantage with carbon capture and storage.

- Another important aspect mentioned in the literature is that IGCC plants are more like chemical plants in that the water used to clean gas creates contamination problems. Therefore, the water with the high pH has to be treated and requires some kind of grey-water treatment facility. Some studies have also shown that capturing CO_2 reduces plant efficiency. Theoretically, IGCC uses less water than a PC power plant but above factors may not result in a less water usage.

Any new revolutionary change to the established industry requires a lot of time, energy and money to implement. IGCC is only beginning to be established; hence many uncertainties and unanswered questions are associated with the technology. At present, IGCC is seen as too risky for private investors, and some additional incentives in the form of enormous subsidies from federal, state and local government are required. In addition, easing the permit process and putting in place a price increase in electricity rates to recover the higher costs has to be judiciously worked out. However, with its higher efficiency potential, lower emission norms and as a remedy to our biggest environmental concern today, greenhouse gas-CO_2, integrated gasification combined cycle appears to be a viable solution over conventional pulverized coal plants.

Chapter 5 – Suggestions for Future Work

There is a lot of potential for future work on this topic. The author found that there is a very extensive scope to elaborate the economical aspect, working technologies, emission standards and emission techniques available. Last but not least is Carbon Capture and Sequestration itself. Each of the above mentioned could be a research topic in itself. Integrated Combined Cycle Power plants can be studied for a comparative construction costs, operation and maintenance costs with due considerations to assumptions made. Surveys can be performed to obtain the actual numbers for the new plants that are under construction as present. Similar studies for new IGCC plants under construction at present can be carried out for emissions and carbon capture when they are operational and producing electricity. Some of the IGCC plants in construction at present are:

- IGCC at Edwardsport, Indiana by Duke Energy and
- Kemper County IGCC Plant, Mississippi Power

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APPENDIX A

(Source: Booras and Holt, Oct 2004)

	PC Subcritical	PC Super-critical	IGCC (E-Gas) W/ Spare	IGCC (E-Gas) No Spare	PC Subcritical	PC Super-critical	IGCC (E-Gas) W/ Spare	IGCC (E-Gas) No Spare
Fuel	PT #8 Coal	PT #8 Coal	PT #8 Coal	PT #8 Coal	IL #6 Coal	IL #6 Coal	IL #6 Coal	IL #6 Coal
Total Plant Cost, $/kW	1,230	1,290	1,350	1,250	1,290	1,340	1,440	1,330
Total Capital Requirement, $/kW	1,430	1,490	1,610	1,490	1,500	1,550	1,710	1,580
Fixed O&M, $/kW-yr	40.5	41.1	56.1	52.0	42.5	42.7	61.9	57.2
Variable O&M, $/MWh	1.7	1.6	0.9	0.9	2.9	2.7	1.0	1.0
Avg. Heat Rate, Btu/kWh (HHV)	9,310	8,690	8,630	8,630	9,560	8,920	9,140	9,140
Capacity Factor, %	80	80	80	80	80	80	80	80
Levelized Fuel Cost, $/MBtu (2003$)	1.50	1.50	1.50	1.50	1.00	1.00	1.00	1.00
Capital, $/MWh (Levelized)	25.0	26.1	28.1	26.0	26.1	27.2	29.9	27.7
O&M, $/MWh (Levelized)	7.5	7.5	9.2	8.6	9.0	8.8	9.8	9.1
Fuel, $/MWh (Levelized)	14.0	13.0	12.9	12.9	9.6	8.9	9.1	9.1
Levelized Total COE, $/MWh	46.5	46.6	50.2	47.5	44.7	44.9	48.8	45.9

Cost, Performance and Economics for Nominal 500MW Power Plants

APPENDIX B

(Source: Nexant Inc, July 2006)

Generation Performance Comparison

	Bituminous Coal				Subbituminous Coal			
Performance	IGCC Slurry Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC	IGCC Slurry Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC
Net Thermal Efficiency, % (HHV)	41.8	35.9	38.3	42.7	40.0	34.8	37.9	41.9
Net Heat Rate, Btu/kWh (HHV)	8,167	9,500	8,900	8,000	8,520	9,800	9,000	8,146
Gross Power, MW	564	540	540	543	575	541	541	543
Internal Power, MW	64	40	40	43	75	41	41	43
Fuel Required, lb/h	349,744	407,143	381,418	342,863	484,089	556,818	517045	460,227
Net Power, MW	500	500	500	500	500	500	500	500

	Lignite Coal			
Performance	IGCC Solid Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC
Net Thermal Efficiency, % (HHV)	39.2	33.1	35.9	37.6
Net Heat Rate, Btu/kWh (HHV)	8,707	10,300	9,500	9,065
Gross Power, MW	580	544	544	546
Internal Power, MW	80	44	44	46
Fuel Required, lb/h	689,720	815,906	752,535	720,849
Net Power, MW	500	500	500	500

Environmental Impact Comparison

	Bituminous Coal				Subbituminous Coal			
Environmental Impact lb/MWh	IGCC Slurry Feed Gasifier	Sub-Critical PC	Super-critical PC	Ultra Super-critical PC	IGCC Slurry Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC
NO_X (NO_2)	0.355	0.528	0.494	0.442	0.326	0.543	0.500	0.450
SO_2	0.311	0.757	0.709	0.634	0.089	0.589	0.541	0.488
CO	0.217	0.880	0.824	0.737	0.222	0.906	0.832	0.750
Particulate Matter[1]	0.051	0.106	0.099	0.088	0.052	0.109	0.100	0.090
Volatile Organic Compounds (VOC)	0.012	0.021	0.020	0.018	0.013	0.025	0.023	0.020
Solid Waste[3]	65	176	165	155	45	73	67	60
Raw Water Use	4,960	9,260	8,640	7,730	5,010	9,520	8,830	7,870
SO_2 Removal Basis, %	99	98	98	98	97.5	87[4]	87[4]	87[4]
NO_X Removal Basis[2]	15 ppmvd at 15% O_2	0.06 lb/MMBtu	0.06 lb/MMBtu	0.06 lb/MMBtu	15 ppmvd at 15% O_2	0.06 lb/MMBtu	0.06 lb/MMBtu	0.06 lb/MMBtu

NOTES:

1. Particulate removal is 99.9% or greater for the IGCC cases and 99.8% for bituminous coal, 99.7% for subbituminous, and 99.9% for lignite for the PC cases. Particulate matter emission rates shown include the overall filterable particulate matter only.
2. A percent removal for NO_X can not be calculated without a basis, i.e. an uncontrolled unit, for the comparison. Also, the PC and IGCC technologies use multiple technologies (e.g., combustion controls, SCR). The NO_X emission comparisons are based on emission levels expressed in ppmvd at15% oxygen for IGCC and lb/MMBtu for PC cases.
3. Solid Waste includes slag (not the sulfur product) from the gasifier and coal ash plus the gypsum or lime wastes from the PC system.
4. A relatively low SO_2 removal efficiency of 87% represents low subbituminous coal sulfur content of only 0.22%. Higher removal efficiencies are possible with increased coal sulfur content.

_______ _ _, Environmental Impact Comparison, continued

	Lignite Coal			
Environmental Impact lb/MWh	IGCC Solid Feed Gasifier	Sub-Critical PC	Super-critical PC	Ultra Super-critical PC
NO_X (NO_2)	0.375	0.568	0.524	0.498
SO_2	0.150	0.814	0.751	0.714
CO	0.225	0.947	0.873	0.830
Particulate Matter[1]	0.053	0.114	0.105	0.100
Volatile Organic Compounds (VOC)	0.013	0.026	0.024	0.022
Solid Waste[3]	218	331	306	291
Raw Water Use	5,270	9,960	9,200	8,710
SO_2 Removal Basis, %	99	95.8[4]	95.8[4]	95.8[4]
NO_X Removal Basis[2]	15 ppmvd at 15% O_2	0.06 lb/MMBtu	0.06 lb/MMBtu	0.06 lb/MMBtu

NOTES:

1. Particulate removal is 99.9% or greater for the IGCC cases and 99.8% for bituminous coal, 99.7% for subbituminous, and 99.9% for lignite for the PC cases. The emission rates shown include the overall filterable particulate matter only.
2. A percent removal for NO_X can not be calculated without a basis, i.e. an uncontrolled unit, for the comparison. Also, the PC and IGCC technologies use multiple technologies (e.g., combustion controls, SCR). The NO_X emission comparisons are based on emission levels expressed in ppmvd at15% oxygen for IGCC and lb/MMBtu for PC cases.
3. Solid Waste includes slag (not the sulfur product) from the gasifier and coal ash plus the gypsum or lime wastes from the PC system.
4. A relatively low SO_2 removal efficiency of 95.8% represents low lignite sulfur content of only 0.64%. Higher removal efficiencies are possible with increased coal sulfur content.

Technology Cost Comparison

	Bituminous Coal				Subbituminous Coal			
Costs*	IGCC Slurry Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC	IGCC Slurry Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC
Total Plant Cost $/ kW	1,430	1,187	1,261	1,355	1,630	1,223	1,299	1,395
Total Plant Investment $/kW	1,610	1,303	1,384	1,482	1,840	1,343	1,426	1,526
Total Capital Requirement $/ kW	1,670	1,347	1,431	1,529	1,910	1,387	1,473	1,575
Annual Operating Cost $1,000s	27,310	27,700	29,000	30,400	29,700	28,300	29,600	31,100

	Lignite Coal			
Costs*	IGCC Solid Feed Gasifier	Sub-critical PC	Super-critical PC	Ultra Super-critical PC
Total Plant Cost $/ kW	2,000	1,255	1,333	1,432
Total Plant Investment $/kW	2,260	1,378	1,463	1,566
Total Capital Requirement $/ kW	2,350	1,424	1,511	1,617
Annual Operating Cost $1,000s	34,000	29,640	30,940	32,440

* All costs are based on 4^{th} Quarter 2004 dollars.